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13. ABSTRACT *(Maximum 200 Words)*

The University of Dayton Research Institute has acquired a digital imaging suite suitable for acquiring images in the visible and mid-infrared wavelengths. The primary equipment in the suite, for infrared imaging, is an Indigo Systems Phoenix camera, with 256 x 320 pixel images. It is sensitive to energy in the 3-5 mm band and has a resolution of 25 mK and a 14-bit dynamic range. A variety of lenses, image processing software, and a flashlamp thermal excitation system are used with the camera for a wide variety of active and passive thermographic nondestructive evaluation (NDE). NDE applications include inspection of composite materials, temperature field mapping, examination of test specimen self-heating, and others. A 3M pixel digital camera and an Infinivar infinitely focusable telescope/ microscope lens are used for visual wavelength imaging with the suite.

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UDRI
UNIVERSITY of DAYTON RESEARCH INSTITUTE

December 12, 2001

Dr. Spencer T. Wu
AFOSR/NA
801 N. Randolph St. Room 732
Arlington, VA 22203-1977

Subject: Grant No. F49620-00-1-0239
Final Report

Dear Dr. Wu:

Please find enclosed three copies of the final report entitled "***Digital Imaging Suite for Nondestructive Evaluation of Materials***", UDR-TR-2001-00137 for the above subject grant number.

Distribution of the copies of the final report and transmittal letter have made as required.

Sincerely,

Robert J. Andrews

Robert J. Andrews, Head
Structural Integrity Division

RJA/mkm

Enclosures

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UNIVERSITY
OF DAYTON
RESEARCH
INSTITUTE

Structural Integrity Division
300 College Park
Dayton, OH 45469-0120
(937) 229-4417
FAX (937) 229-3712

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UDR-TR-2001-00137

Report

DIGITAL IMAGING SUITE FOR NONDESTRUCTIVE EVALUATION OF MATERIALS

October 2001

NOTICE

Approved for Public Distribution.

Digital Imaging Suite for Nondestructive Evaluation of Materials

Final Report

Grant No. F49620-00-1-0239

October 2001

Prepared for:

Air Force Office of Scientific Research
801 N. Randolph St.
Room 723
Arlington, VA 22203-1977

Prepared by:

James Sebastian, P.E.

University of Dayton Research Institute
STRUCTURAL INTEGRITY DIVISION
300 College Park
Dayton, OH 45469-0120

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Section 1
Introduction

As proposed, the University of Dayton acquired a digital imaging suite consisting of an infrared camera and associated peripheral equipment under funding provided by AFOSR through the FY2000 Defense University Research Instrumentation Program. The imaging suite is being used to support a number of current and planned programs for the DOD and other sponsors.

The imaging suite resides in the Material Characterization Laboratory of the University of Dayton Research Institute (UDRI) Structural Integrity Division. The equipment is available for graduate students who may wish to use the equipment to support thesis or dissertation research efforts, especially those involved in the University's Center for Material Diagnostics MURI program on nondestructive evaluation. University of Dayton research staff are using the equipment to support research programs sponsored by the DOD, other government agencies, and industry. Close collaboration is being maintained between the various researchers using the system in order to maximize the benefits from its acquisition.

Section 2
Equipment Purchased

2.0 INTRODUCTION

A number of components were purchased for the digital imaging suite. This section contains a description of all the major components purchased for the imaging suite. In addition, Appendix A contains a table listing each major and minor component with manufacturer.

2.1 INFRARED CAMERA SYSTEM

A Phoenix infrared camera system made by Indigo Systems Corporation, Santa Barbara, CA, was purchased for approximately $83,000. Acquiring this system was the primary purpose for the DURIP funding request, and required the largest portion of the available funds. The camera has a sensitivity of 25 mK in the 3-5μm mid-infrared band. The detector is an InSb focal plane array capable of producing a 14 bit grayscale image, 320 x 256 pixels, at an imaging rate of 60 Hz. Faster rates may be obtained by reducing the number of pixels imaged, and synchronization of image acquisition with an external trigger is possible. The camera system consists of a Phoenix camera head, Phoenix real time imaging electronics, and Talon Ultra image acquisition software running on a Windows NT microcomputer. Liquid nitrogen cooling was chosen instead of an integrated cooler because it has the potential for a longer camera life. The camera head is shown in Figure 1.

2.2 INFRARED MICROSCOPE

An infrared microscope and a 1X objective for use with the infrared camera were purchased from Diversified Optics Inc. (DIOP), Salem, New Hampshire, for approximately $12,000. The microscope allows small regions of a specimen to be imaged at high resolution. With the 1X objective, an area 9.6mm x 7.6 mm is imaged, with each pixel on the image corresponding to a 30 μm square on the sample being imaged. 3X and 4X objectives are

available for this microscope if additional magnification is needed in the future. The infrared microscope lens will be used for imaging small regions of a sample; it will be especially useful for imaging developing cracks at stress concentrations and for localized inspection of composite materials. The microscope with 1X objective is on the camera in Figure 1.

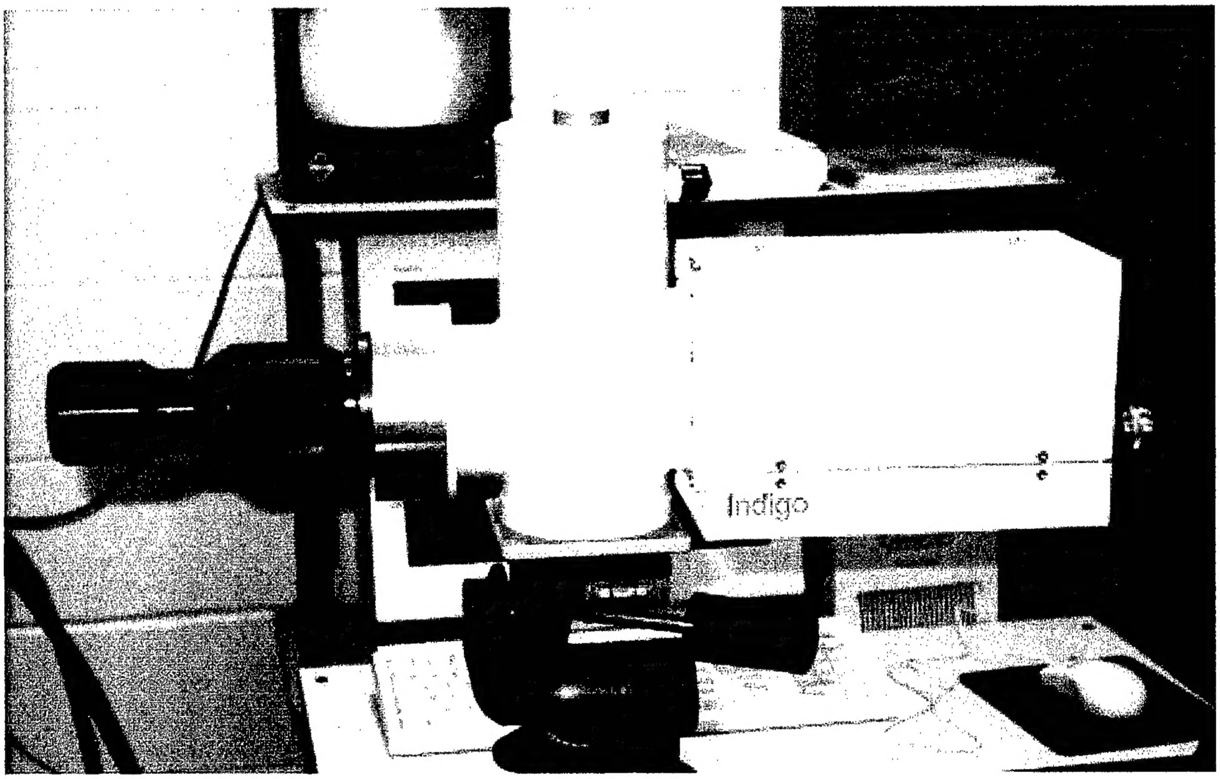

Figure 1. Indigo Systems Infrared Camera With DIOP Microscope Lens

2.3 INFRARED LENS

A 50mm focal length infrared lens for the Phoenix camera was purchased from Janos Technology, Townshend, VT. This lens has an 11° horizontal field of view and may be focused for an object distance from infinity down to 0.43m. A set of extender rings allows the lens to be focused at much closer distances with correspondingly smaller fields of view. This lens will allow for general imaging for thermographic evaluation of materials and samples. Specifically, UDRI expects to use active thermography to image advanced ceramic matrix composites and polymer matrix composites being developed for Air Force use. This will complement UDRI's

other NDE inspection capabilities, while enabling the inspection of materials such as certain ceramic composites which are degraded by water and cannot be scanned ultrasonically.

2.4 PHOTOGRAPHIC FLASHLAMPS

Photographic flashlamps and a 4.8kJ power supply from Speedotron, Chicago, IL were purchased to provide impulse heating of samples for thermographic evaluation. The combination of the #4803cx power supply and 2 #105 light units allows approximately 70% of the energy stored in the lamps to be delivered in less than a millisecond. Short duration, high energy heating is a key to obtaining good depth and spatial resolution when imaging a sample. The power supply and one of the two flashlamps are shown in Figure 2. Protective eyeware has been purchased, and a room has been set aside for using the flashlamps.

Figure 2. Speedotron Power Supply and Flashlamp

2.5 DIGITAL CAMERA

A Canon Powershot G1 digital camera was purchased for the visible imaging portion of the suite. This camera can obtain images at resolutions up to 2,048 x 1,536 pixels. This camera has a unique combination of interfaces which allow remote operation from a PC and continuous sending of video images, allowing it to be used remotely on a microscope. Adapters were purchased so that the camera can be used with a trinocular microscope in the Material Characterization Laboratory as well as with the Infinivar microscope described below. This camera was used to take the pictures in Figures 1, 2, and 3.

2.6 IFINIVAR MICROSCOPE

A Infinivar video microscope was purchased from the Infinity Photo-Optical Company, Boulder, Colorado. It is continuously focusable from infinity down to 10mm working distance. This instrument may be used bench- mounted as a microscope to approximately 200x with the Canon digital camera. It may also be used as a macro lens for a wider field of view, or as a telescope lens. A targeted application for this system is the measurement of cracks in a crack growth test using image processing to automatically determine crack length. The Infinivar microscope is shown on its mounting arm in Figure 3. This configuration allows a great deal of freedom of motion above the workbench, including horizontal use; the arm may be dismounted from the wall and clamped to a tabletop or fixture for use elsewhere in the lab, such as at a servohydraulic test frame.

2.7 IMAGING MICROCOMPUTER, HARDWARE, AND SOFTWARE

A separate Gateway microcomputer was purchased to serve as a supervisory system for the visual imaging system and to receive images from the digital camera via Universal Serial Bus and analog video. This computer is used for image analysis and archiving, in addition to its active role in remote camera operation. Labview software from National Instruments allows

control of the system by anyone with a minimal programming and data acquisition background. Adobe Photoshop provides additional options for image manipulation.

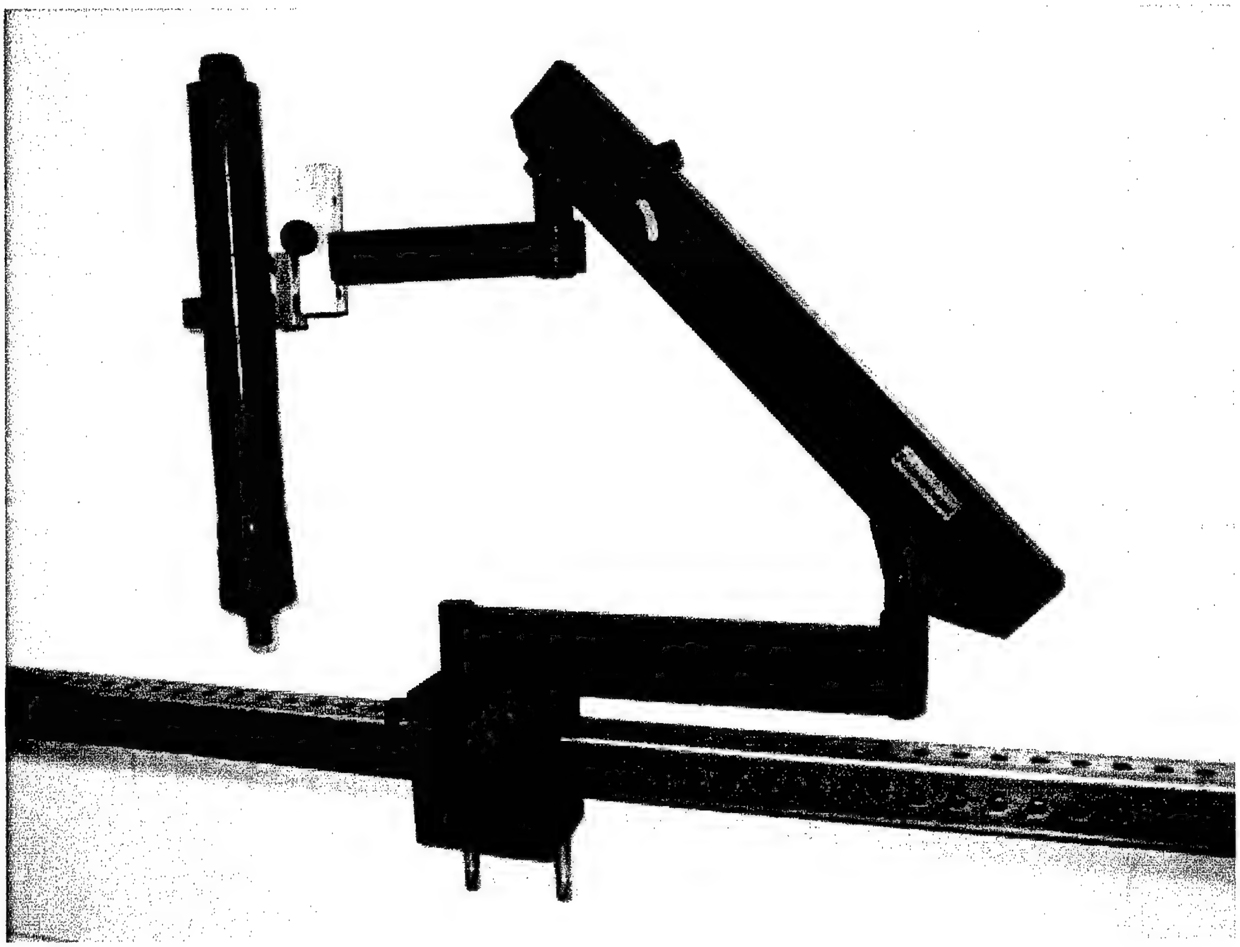

Figure 3. Infinivar Microscope

Section 3
Programs Using The Equipment

3.0 THERMAL EVALUATION OF FRETTING FATIGUE FIXTURE

The University of Dayton has a number of on-site contracts to support researchers at the Air Force Research Laboratories. In support of one of these efforts in the Materials Directorate, the infrared imaging system was transported to Wright-Patterson Air Force Base temporarily. Ongoing research on contract #F33615-98-C-5214, "Life Prediction Methodologies for Aerospace Materials" includes an investigation of fretting fatigue in engine alloys. Fretting is a phenomenon where very small relative motions between two parts cause surface damage, which in turn creates initiation site for fatigue cracks, reducing the useful life of the part. Theory states that this occurs at room temperature, but the rubbing action of the parts intuitively points toward the generation of heat from friction. Using a high magnification lens on the infrared camera, no heat rise was detected in the fretting area on the test stand, confirming the researcher's hypothesis. Earlier insertion of thermocouples for this purpose had led to concerns about influencing the actual test conditions.

3.1 ULTRASONIC FATIGUE DAMAGE ACCUMULATION

A subcontract entitled, "Fatigue Damage Evaluation Using 20 kHz Machine" under Federal contract# F33615-97-D-5271 was completed by the University of Dayton. The aim of the subcontract was to construct an ultrasonic fatigue system capable of accumulating fatigue cycles in aerospace alloys at 20kHz. As part of this effort, the Indigo infrared camera was used to quantify heating in the specimen. As shown by the brighter areas in Figure 4, the primary locations for heat generation were in the highly stressed gauge section and at the ends of the specimen where it interfaces to a resonant booster system. The test system has since been delivered to the Air Force Research Laboratories, but the camera may be used for further investigative work with the system.

Figure 4. Specimen Self-Heating at 20 kHz

3.2 TEST SPECIMEN CHARACTERIZATION

The Indigo infrared camera has been used to look at a number of test panels and specimens of various materials and geometries. The materials include ceramic composites, graphite-epoxy composites, composite patches on aluminum, and corrosion of aluminum under protective coatings. Figure 5 shows a sequence of images from a damaged CMC specimen, with the delaminated area remaining hot (white) as heat from the flashlamp conducts away from the surface in the undamaged regions of the specimen. Figure 6 shows thermal images of a test panel before and after an impact test. Figure 7 shows a portion of a graphite-epoxy panel where random fiber orientation and distribution was successful. Figure 8 shows warm areas (blue) corresponding to "good" areas of a coated aluminum panel. It is expected that future work will be performed with the infrared imaging system in many of these areas.

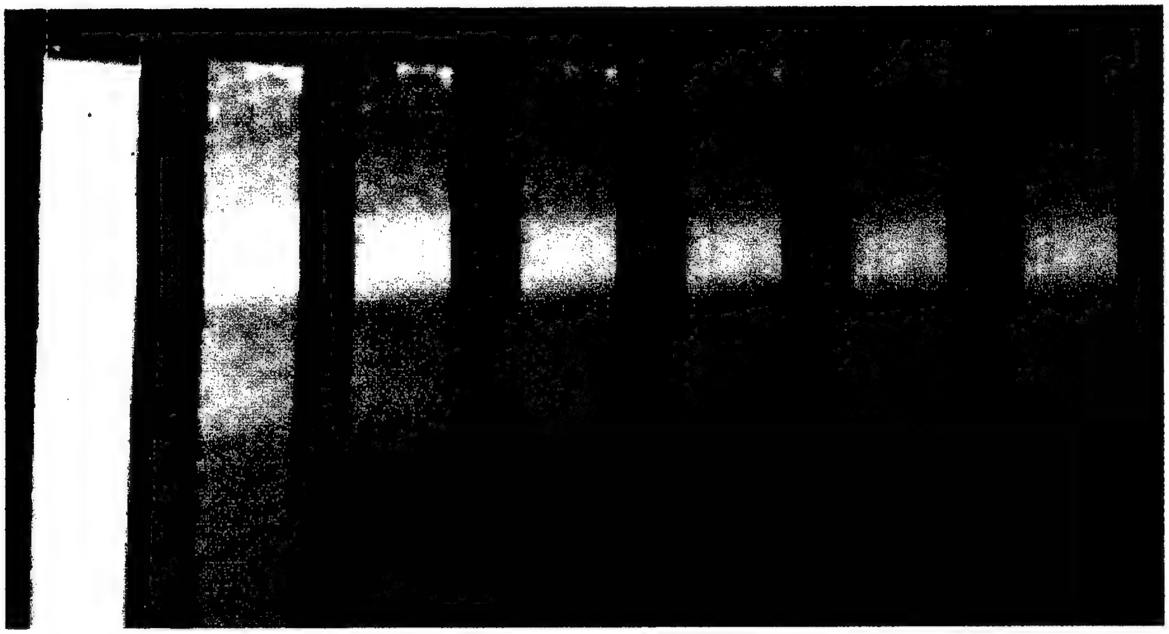

Figure 5. Ceramic Matrix Composite Specimen

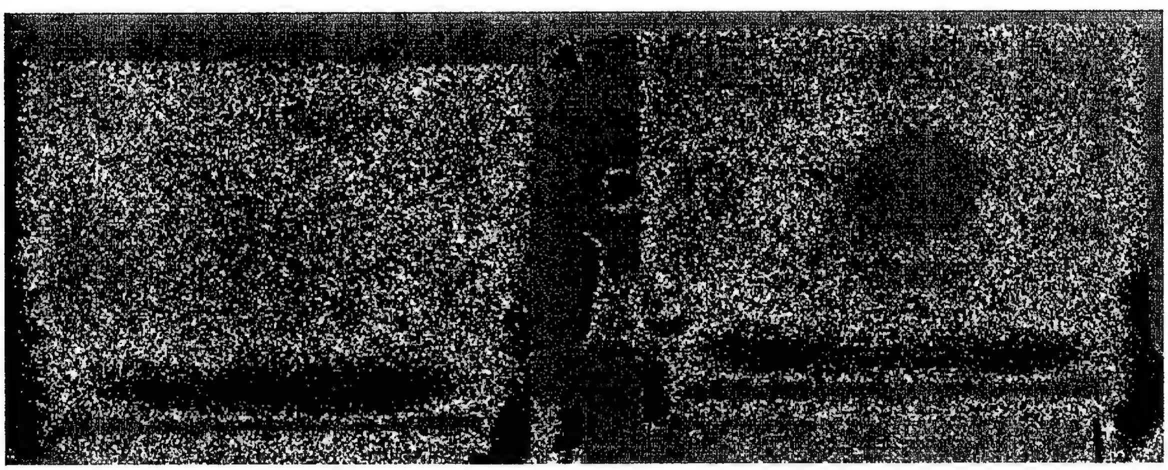

Figure 6. Test Panel Before and After Impact

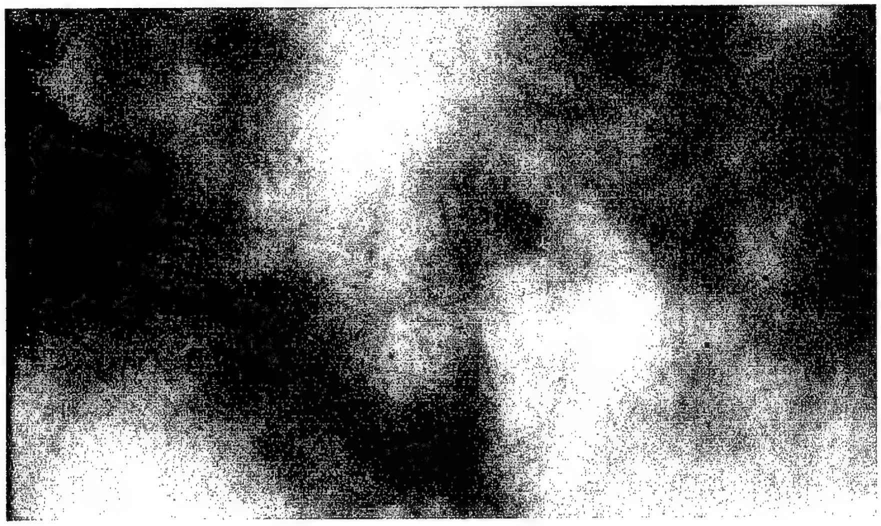

Figure 7. Random Fiber Orientation in PMC

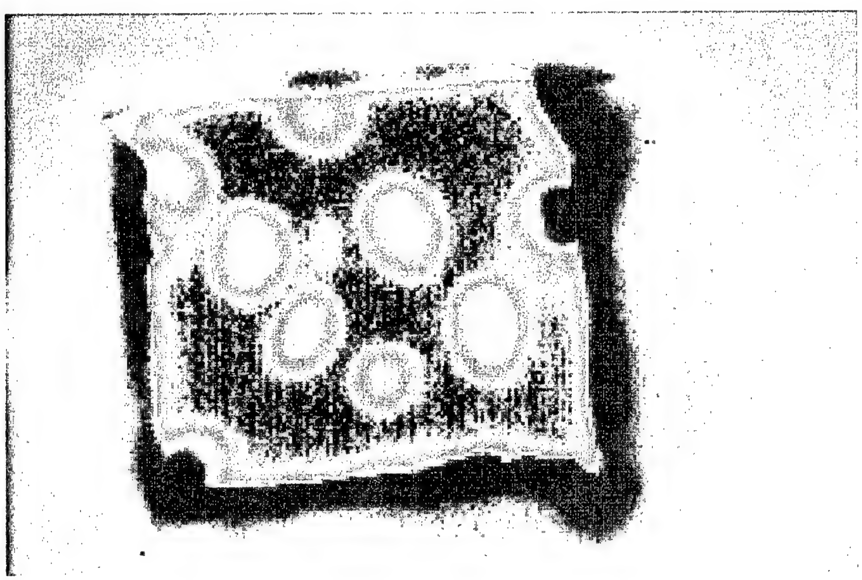

Figure 8. Failing Areas of Coating

3.3 NONDESTRUCTIVE EVALUATION OF REPAIR PATCHES

The infrared camera is currently being used to provide in-situ nondestructive evaluation of bonded repair patches in UDRI's Structures Test Laboratory as part of a "Composite Repair of Aging Structures" research program. In this effort, aluminum sheet specimens are damaged by

local thinning to simulate corrosion or notching to simulate a crack. Composite repair patches are applied over the damaged areas, and the specimens are subjected to mechanical loading to simulate in-service conditions.

The infrared camera was needed to provide images of the disbonded area, if any, beneath the patches as the test progressed. Heat is applied to the back side of the specimen while the front is imaged; any disbonds do not conduct the heat well and are revealed. This procedure is repeated several times during a test in order to detect the onset of damage and to monitor its progression. Ultrasound, a secondary choice for these evaluations, would have been significantly more difficult and time-consuming to apply due to the large specimen area and the need for more extensive data analysis.

3.4 CRACK-LIKE FLAW DETECTION

As part of the "Turbine Engine Support Initiative", the infrared camera is being used to evaluate two new methods of whole-field nondestructive evaluation. These methods are directed at using noncontact imaging to look for cracks at locations where contact eddy current probes have difficulty. Test methods include both active heating with an external source, and mechanical excitation to provide internal temperature gradients at the specimen surface.

Section 4
Future Uses For The Equipment

In addition to the ongoing programs noted above, we anticipate significant future use of the infrared imaging equipment, especially in the following areas:

- Whole-field NDE methods development
- Ultrasonic fatigue damage accumulation and heating
- Ceramic matrix composite characterization and damage evaluation following mechanical testing
- Polymer matrix composite characterization and damage evaluation following mechanical testing or impact testing
- Coatings evaluation for thickness and bond integrity
- Whole-field temperature mapping

Similarly, there is substantial ongoing and future use for the visible imaging portion of the equipment. This includes:

- General laboratory imaging, such as documentary photographs of test apparatus and specimens.
- Photomicrography for metallurgical and similar evaluation.
- Experimentation with the automation of optical crack length measurement in fatigue crack propagation tests of aerospace and other alloys.
- Documentation and analysis of images from fluorescent dye penetrant used to detect surface flaws in materials.

Section 5
Conclusions

The acquisition of the digital imaging suite described in this report has significantly enhanced the nondestructive evaluation capabilities of the University of Dayton's Materials Characterization Laboratory. Imaging components operating at visible wavelengths complement the current capabilities, while adding new possibilities for digital image acquisition, test automation, and long-distance microscopy.

The infrared imaging portion of the suite, comprising the majority of the expended funds, provides a cutting-edge capability to the entire scientific community of the University of Dayton. To date, it has been used in four locations within the University, in addition to one location at Wright-Patterson AFB. The infrared imaging components have been chosen to provide a long useful life, and are expected to be used for many additional projects within the University. The majority of these projects are expected to be Air Force sponsored, but the equipment will also be available for use involving other research. The infrared equipment should be a good tool for graduate students who choose to perform research requiring this type of research.

The University of Dayton would like to thank the Air Force Office of Scientific Research and the Department of Defense for making the acquisition of this equipment possible.

Appendix A

Detailed list of equipment purchased

The digital imaging suite consists of two subsystems, for infrared and visible image acquisition. Each subsystem is an individually accountable piece of equipment. Subsystem costs include component costs, materials, equipment rental, and cost-shared labor.

The Infrared Imaging Subsystem was built by the University of Dayton as a laboratory-constructed project for approximately $116,800. Components are shown in the table below.

Infrared Imaging Subsystem Components	Manufacturer
Phoenix 320x256 Infrared Camera	Indigo Systems
Phoenix Infrared Camera Real Time Imaging Electronics	Indigo Systems
Talon Ultra Image Acquisition Hardware and Software	Indigo Systems
Talon Light add-on	Indigo Systems
Infrared Lens- 50 mm focal length	Janos Technology
Bayonet Lens Spacer kit -1/4", 1/2", 3/4", 1"	Janos Technology
Infrared Microscope Body	Diversified Optical Products Inc
Infrared Microscope Objective-1X	Diversified Optical Products Inc
Infrared Microscope bayonet mount	Diversified Optical Products Inc
Video Monitor for IR camera	Pelco
Bogen #3246 tripod leg set	Bogen
Bogen #3057 tripod 3-way head	Bogen
4 quart LN2 dewar	Fisher Scientific
4803cx Flash Power Pack (to 4800 W-s)	Speedotron
2 cable #105 flash lamp, quantity two	Speedotron
reflector for #105 flash lamp, quantity two	Speedotron
Flash Power Pack Remote Control	Speedotron
Computer cart	Global Computer
surge suppressor power strip	Global Computer
50.8mm sapphire window	Edmund Scientific

The Visible Imaging Subsystem was built by the University of Dayton as a laboratory-constructed project for approximately $14,200. Components are shown in the table below.

Visible Imaging Subsystem Components	
Powershot G1 3.3 Megapixel digital camera	Canon
Infinivar continuously variable focus microscope	Infinivar
T36 extension tube	Infinivar
T30 extension tube	Infinivar
M62 eyepiece holder	Infinivar
10x eyepiece	Infinivar
MS Plan Microscope Objective	Olympus
Image acquisition and processing microcomputer	Gateway 2000
PCI-6503 Digital I/O Board	National Instruments
PCI-1411 Analog Image Acquisition Board	National Instruments
Application Development Software- Labview Upgrade	National Instruments
LabView Application Builder	National Instruments
IMAQ Vision Builder	National Instruments
Photoshop Image Processing Software	Adobe
(2) 25' Cat 5 Ethernet cable	Dartek
Articulating Arm Stand	Howard Electronic Instruments
150W fiber optic illuminator	Howard Electronic Instruments
dual branch semi-rigid light guide	Howard Electronic Instruments
spare bulb for illuminator	Howard Electronic Instruments
T-mount eyepiece mount	Edmund Scientific
adapter post	Parts Unlimited
microscope adapter to translation mount	Parts Unlimited
Thick base single axis movement translation mount	Edmund Scientific
Cross slide vise	Harbor Freight Tools
Adapter- camera to 49mm F	Lensmate
49mm plastic lens cap	Lensmate
Adapter- 49mm M to 42 mm F (T-mount)	CKC Power
perforated steel tube for microscope wall mount	McMaster-Carr
5/8" 303 SS rod for microscope mount	McMaster-Carr
lag screws	McMaster-Carr
nylon thumb screws	McMaster-Carr
Flash protective goggles	McMaster-Carr
100W fan cooled ultraviolet lamp	VO Baker